Observations of mesospheric ozone depletion during the October 28, 2003 solar proton event by OSIRIS

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[1] One of the largest solar proton events in the past thirty years took place on October 28, 2003 and had a significant impact on the Earth's middle atmosphere. The incoming protons produce significant amounts of HO_x constituents in the mesosphere and upper stratosphere that lead to ozone depletion. For 11 hours during the solar proton event the OSIRIS instrument on Odin measured high spatial resolution profiles of the oxygen infrared atmospheric band at 1.26 microns which under sunlit conditions can be used as a direct proxy for ozone. Ozone depletion is observed across the southern polar cap for the duration of the observations and extends to latitudes as far north as 45°S. OSIRIS observed significant ozone depletion between 50 and 80 km with a maximum value of 75% around 65 km. The actual maximum depletion could have been even greater as observations ceased while the depletion was still increasing. Citation: Degenstein, D. A., N. D. Lloyd, A. E. Bourassa, R. L. Gattinger, and E. J. Llewellyn (2005), Observations of mesospheric ozone depletion during the October 28, 2003 solar proton event by OSIRIS, *Geophys. Res. Lett.*, *32*, L03S11, doi:10.1029/2004GL021521.

1. Introduction

[2] A series of solar flares associated with coronal mass ejections occurred in late October 2003 and caused a major Solar Proton Event (SPE) on October 28. The X-17 class event is the largest solar proton event since 1962. It is well known that incoming high energy protons produce significant amounts of HO_x (H, OH, HO_2) and NO_x (N, NO, NO_2) constituents in the polar middle atmosphere that, in turn, directly influence atmospheric ozone density [*Swider and Keneshea*, 1973; *Frederick*, 1976; *Solomon et al.*, 1983; *Jackman and McPeters*, 1985]. The HO_x constituents are quite short-lived and lead to large, short-term ozone decreases in the mesosphere and upper stratosphere, typically lasting a few hours or days. The NO_x constituents are much longer-lived and can influence the stratospheric ozone density over periods of months to years [*Rusch et al.*, 1981; *Jackman et al.*, 1990; *Reid et al.*, 1991; *Jackman and Fleming*, 2000]. Several models currently exist which calculate the response of the middle atmosphere to SPEs [*Jackman et al.*, 1995; *Krivolutsky et al.*, 2003; *Verronen et al.*, 2002] and, in particular, *Jackman et al.* [2001] convincingly modeled the SPE ozone depletion and NO_x enhancement measured by the NOAA 14 SBUV/2 and HALOE instruments in July 2000.

[3] The OSIRIS instrument on the Odin satellite was operational during the SPE of October 2003 although coverage was not as complete as normal due to the harsh operational environment associated with the geomagnetic storm. OSIRIS measured line-of-sight height profiles of the Oxygen InfraRed Atmospheric (OIRA), or $O_2(a^1\Delta_g)$, band mesospheric airglow emission once every two seconds with a height resolution of 1 km. This emission is an accurate proxy for mesospheric ozone during sunlit and twilight conditions as its dominant sources are related to the photolysis of ozone [*Mlynczak et al.*, 1993]. Consequently the OSIRIS dataset affords a unique opportunity to study the time evolution of mesospheric ozone during the October 2003 SPE with unprecedented height, time and spatial resolution.

2. The Measurements

[4] The OSIRIS InfraRed Imager (IRI) [*Llewellyn et al.*, 2004] consists of three vertical imagers. An imager simultaneously measures along 100 lines of sight, each separated by approximately 1 km tangent altitude. This study only considers the line-of-sight brightness from the OIRA band measured over a 10 nm passband centred at 1.263 microns. The data from each orbit are used in a tomographic retrieval scheme [*Degenstein et al.*, 2003, 2004; *McDade and Llewellyn*, 1991, 1993; *McDade et al.*, 1991] to retrieve the two-dimensional OIRA band Volume Emission Rate (VER) profile contained within the Odin orbit plane. The VER profiles are produced at 1 km height resolution every 0.2° along the orbit track. The spatial resolution achieved with this two-dimensional technique is easily adequate for the large scale size features discussed later in this work.

[5] Odin [*Murtagh et al.*, 2002] is in a dusk-dawn (ascending-descending node), sun-synchronous, 98° inclination, near circular orbit at a height of approximately 600 km above the surface of the Earth. The OSIRIS instrument looks only in the orbit plane so the highest latitude sampled is approximately 82°. This is true in both hemispheres and the latitudinal coverage is constant from orbit to orbit. However, the solar conditions at each point along the orbit vary significantly throughout the year. At the time of the solar proton event the southern hemisphere portion of the Odin orbit was illuminated. The solar conditions for the time of interest were such that at the highest southern latitude, 82°, the solar zenith angle was approximately 84° and evening twilight had just begun.

[6] On October 28, 2003 the IRI began normal operations approximately 6 hrs after the SPE began. Prior to this, Odin was operating in a special mode and no data immediately

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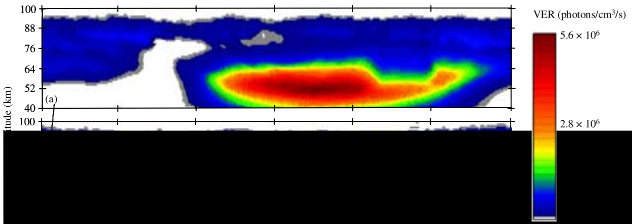

Figure 1. Two-dimensional plots of retrieved OIRA band volume emission rate profiles for the last available SPE orbit (a) and the first available orbit after the SPE (b), the latter is considered as the baseline orbit. The start times for the orbits are 2003/10/29 04:29:40 UTC and 2003/10/31 19:13:22 UTC for panels a) and b) respectively.

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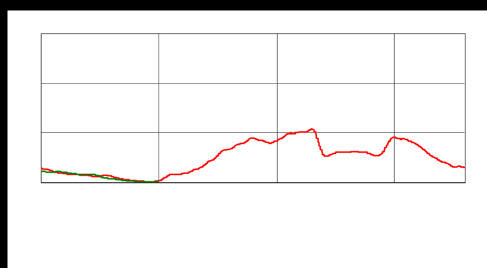

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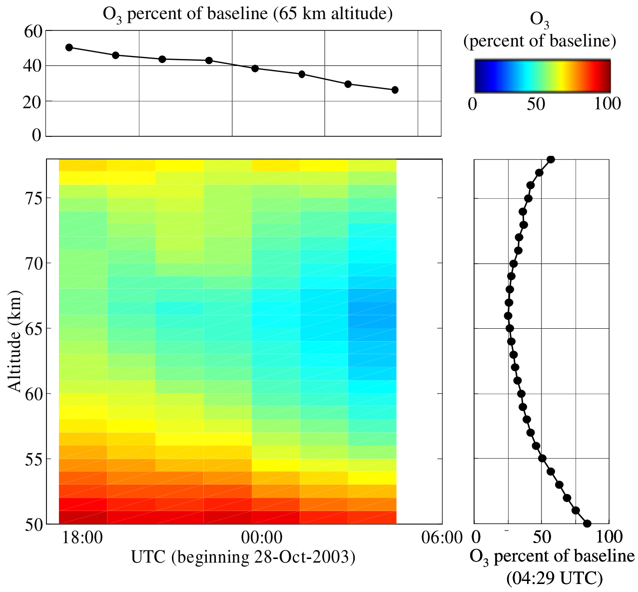


Figure 3. The two-dimensional plot and associated cross sections indicate the time evolution of the fractional ozone depletion at 82° south. A continuous depletion with time that is maximum just above 65 km is evident.

collected during the storm period where the vertical profiles are separated by 1:36:30 in UT but are made at the same local time and latitude. The cross sections displayed in Figure 3 show a steady decrease in ozone with time that is layered with a maximum around 65 km.

[13] Figure 4 shows a polar plot of the spatial extent of the ozone depletion region along with its temporal evolution. Since orbits intersect each other at different times the storm data are separated into two polar plots, one for data collected on the ascending tracks of the orbits and the other for the descending tracks. The orbit tracks are indicated on both plots and the results between the tracks are produced with a cubic spline interpolation. Although these plots are a useful visual aid, care must be exercised as they blur the spatial and temporal components of the effects of the SPE. For each latitude time increases with longitude in a counter clockwise sense.

3. Discussion

[14] The destruction of mesospheric ozone by the SPE is readily evident in the OSIRIS data set and provides a beautiful example of the phenomenon. The physical processes responsible for the destruction are thought to be well known: the SPE causes the production of water cluster ions that undergo dissociative recombination to form OH and H that, in turn, catalytically destroy ozone [*Solomon et al.*, 1983]. The reaction rates are relatively rapid and the ozone depletion only persists for a few hours after the end of the SPE.

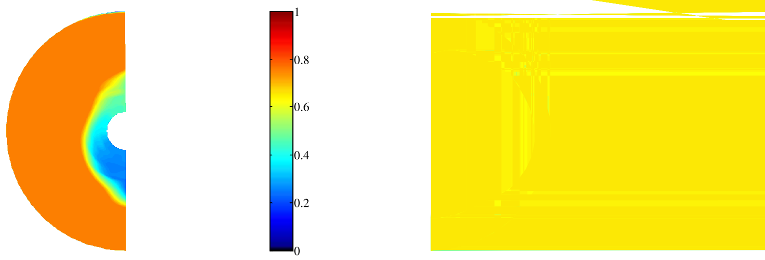
[15] The hemispherical, polar plots shown in Figure 4 are quite remarkable in that they are devoid of significant structure within the polar cap. Some of this smoothness is due to the spline interpolation of the coarse longitudinal sampling but this is certainly not the case for latitudinal slices along the orbit track which have an intrinsic sampling resolution of 0.2°. Clearly the proton precipitation was relatively uniform across the entire polar cap region and produced similar atmospheric responses at all locations. The lower boundary of the proton precipitation is readily identified from Figure 4 as the transitional region from significant ozone depletion to minor depletion and is seen to extend equatorward to 45–50°S.

[16] The OSIRIS data, due to operational reasons, are only available during the peak hours of the storm but nonetheless clearly show the time evolution of the mesospheric ozone in response to the SPE. The OSIRIS data begin approximately 6 hours after the start of the SPE event as recorded by the GOES 11 Proton Flux measurements (http://solar.sec.noaa.gov). By this time the mesospheric ozone density at 65 km (~0.17 hPa) had already decreased to 50% of its normal value in response to the SPE and continued to decrease for the next 11 hours of OSIR[illegible] observations. When OSIRIS was turned off, the ozone [illegible] depleted to 75% of normal values at 65 km and show[illegible] sign of abatement. If the downward trend continu[illegible] observed rate then the ozone density at 65 km w[illegible] reached zero by October 29, 2003 18:00 UT. By [illegible] when OSIRIS was next powered on, the meso[illegible] had completely recovered from the entire ef[illegible] as expected.

[17] The altitude of maximum ozone [illegible] icantly below the altitude measured [illegible] *Jackman et al.* [2001] for the SPE of [illegible] event HALOE observed a maximum dep[illegible] altitudes centered on 0.05 hPa (73 k[illegible] observed a maximum depletion of 75%[illegible] SPE of October 2003. The 8 km differe[illegible] the resolution of both instruments and m[illegible] result from the different response of t[illegible] differing proton spectra. However, it is n[illegible] simple inspection of the GOES 11, 5 m[illegible] that one of these SPE is dominantly stron[illegible] A proper resolution of the issue woul[illegible] modelling of the mesospheric ion and ne[illegible] the October SPE which is beyond the sc[illegible]

4. Conclusions

[18] The OSIRIS instrument on Od[illegible] dimensional OIRA band VER profiles[illegible]



Hemisphere for 11 hours during the October 2003 SPE with a height resolution of 1 km and a separation of 0.2° along the orbit track. A uniform depletion of the VER was observed across the entire polar cap region throughout this period. This region extended as far north as 45°S. We conclude there was a corresponding depletion of ozone in the same region as this emission is a direct proxy for ozone under sunlit conditions.

[19] We have quantified the amount of ozone depletion using a simple photochemical model and referencing baseline data collected two days after the storm. Ozone depletion was observed from 50 to 80 km altitude with maximum depletion occurring around 65 km. The ozone depletion at 65 km was 50% at the start of OSIRIS observations, approximately 6 hours after the SPE onset, and steadily increased to 75% when OSIRIS was turned off 11 hours later. There was no indication that the depletion had stabilized and may have continued to increase after observations ceased.

[20] The observations appear to be in qualitative agreement with previous modelling studies as several models have predicted mesospheric ozone depletions greater than 70%. However, the height of maximum depletion observed by OSIRIS on October 28 2003 was 65 km while model predictions and measurements for previous storms generally place this height closer to 73 km (0.05 hPa).

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